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Improving design safety of tractor-trailers by upgrading towing couplers

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Abstract. One major way of increasing efficiency in production, construction and agriculture industries is to use motor- and tractor-trailers for transportation needs. At the same time, a tractor-trailer is a complex and less maneuverable machine in comparison with a single vehicle. Exceeding the velocity regime, especially in the case of tractor-trailers, leads to a loss of stability during linear motion, on curvilinear sections of the trajectory or in complex traffic conditions. Speed limit is a standard prevention method; however, it does not guarantee any acceptable result. Other ways of resolving this issue have almost exhausted their potential. It should be noted that solving this problem is further complicated by a lack of a unified road-movement theory for tractor-trailers – thus, mainly restrictive measures are used. The authors suggested a hypothesis on possible improvement of tractor-trailer safety by means of increasing their motion stability via upgraded design characteristics of towing tractor-trailer couplers. The higher stability would be achieved by raising the damping factor of transverse oscillations by applying lateral disturbing forces. The authors proposed over 55 technical solutions, all protected by certificates of authorship in engineering, of upgrading the towing couplers and providing the increase of tractor-trailer operation safety in various road conditions.

1. Introduction

One major way of increasing efficiency in production, construction and agriculture industries is to use motor- and tractor-trailers for transportation needs. It allows one to substantially expand the range of transported cargo and special equipment. Heavy indivisible equipment, long-measuring objects (timber, pipes, etc.), crawler-type vehicles, excavators can be transported over highways or earth roads only with the help of tractor-trailers. A tractor-trailer is as powerful as it is complex and usually less maneuverable in comparison with a single vehicle. There are certain peculiarities of driving tractor-trailers and special rules of their operation and storage.

In recent years, designers, production engineers, automobile-industry specialists, research-institute and test-site employers have been actively working on new trailers and semitrailers with improved technical properties and design safety.

Driving a tractor-trailer on a motor road is not a very common practice. Tractor-trailers are mostly utilized for harvesting and transportation of the crop among agro-industrial organizations, in communal services, as intraplant transport and in other fields where high velocity is of lesser importance. At the same time, new energy-saturated wheeled tractors, which come into operation, have higher velocity characteristics (over 80 km/h) and may well compete with motor-trailers on a highway. The velocity record of a wheeled tractor, achieved in Norway, is at 130 km/h. Unfortunately, modern trailers, in comparison with tractors themselves, have not been as well upgraded. Their technical properties (linear



motion stability, maneuverability and others) and design safety do not allow one to use the velocity of tractors to its full potential. Thus, exceeding the velocity regime, especially in the case of tractor-trailers (or other vehicles with trailers), leads to overturning, mostly during curvilinear motion or with other complications present (fog, sleet, road dents and others).

Accordingly, moving vehicles are both harmful and dangerous for the human health and capable of causing irreparable damage to the environment (consequences of an accident sometimes are more harmful than the accident itself). Performance characteristics of motor- and tractor-trailers, such as maneuverability and trajectory motion stability, are way below those of a single vehicle, which has negative impact on safety and work environment of drivers.

As a result, higher demands are placed on design safety of tractor-trailers. The design safety itself is an ability to prevent traffic accidents or reduce the weight of their consequences, not harming people and environment. There are four types of design safety: active, passive, post-accident and ecological ones.

Better active design safety is achieved in particular by improving such a factor as the tractor-trailer stability [1], which would allow to maintain linear motion despite the disturbing forces that provoke skidding or overturning, especially at high speeds. Here the concept of stability is used only for linear motion of a vehicle.

Statistics, given by GIBDD (the General Administration for Traffic Safety of the Ministry of Internal Affairs of Russia) of Sverdlovsk region, on traffic accidents in 2017 when trailers were involved showed (Figures 1, 2) that 2120 accidents in total were recorded, 108 among them involved freight motor transport and 87 of those involved trailers, which was 80.5%. But as the number of trailers on the road is a lot less than the number of single vehicles, it really manifests higher danger from tractor-trailers when it comes to road accidents.

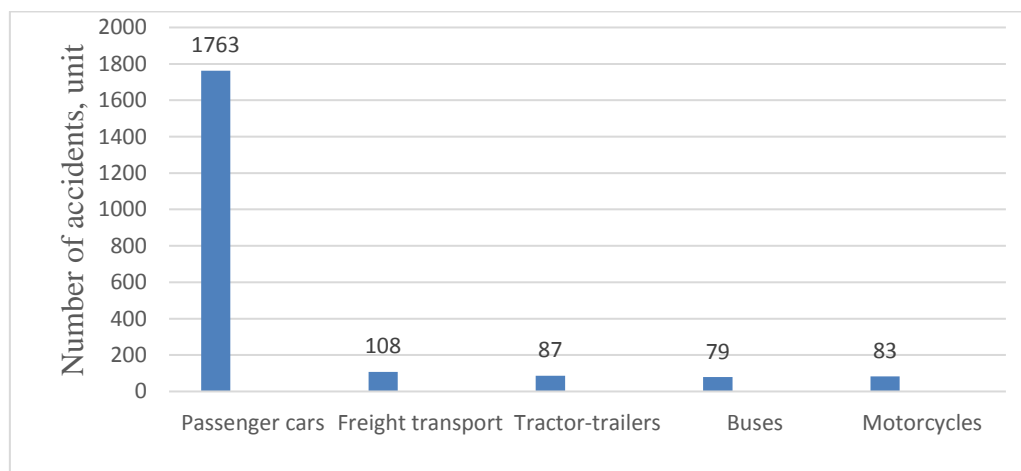


Figure 1. Accident rate on the roads of Sverdlovsk region in 2017.

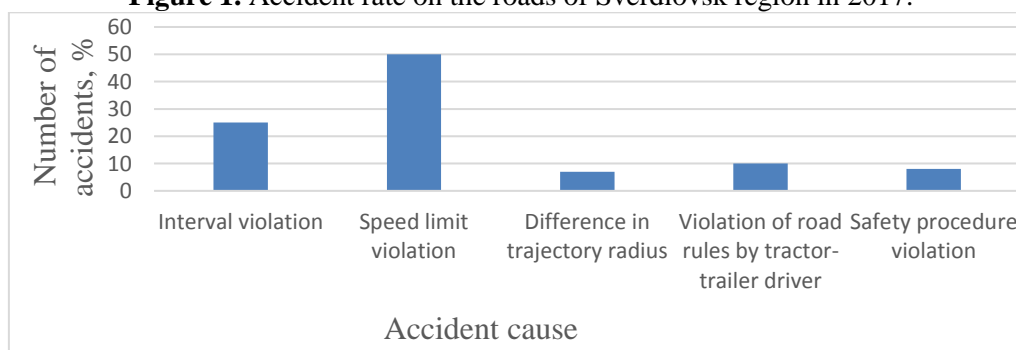


Figure 2. Statistics on accidents which involved freight transport with trailers on the roads of Sverdlovsk region in 2017.

The statistics show that most trailer-related accidents happen due to speed limit violation (under 90 km/h for highways and 70 km/h for other roads) and violation of the interval between a trailer and a following vehicle.

Significant lengths of tractor-trailers and presence of movable joints in the plane of motion between a towing tractor and connected trailer parts lead to high accident rate at maneuvering. Besides, maneuvering, especially at high speeds, increases lateral reactions of road surface and inertial lateral forces which cause movement instability and decrease resistance to overturning. In addition to that, cornering and lane changing require significantly more time in comparison with a single-vehicle case. When the lane is changed, a tractor-trailer occupies two traffic lanes, and, due to a folding between the tractor and its trailer, a «pocket» is formed for vehicles following behind in the same direction.

Basic sizes of tractor-trailers are limited by international standards and additional decrees of the Russian Federation for the sake of their operation safety. In Europe drivers are licensed to use a tractor-trailer which is no longer than 16.5 m. Those limits extend also on the trailer itself are no more than 12 m in length. The total length of a tractor-trailer in Russia is limited by 20 m. Due to these restrictions, cabover tractors, whose cabin and motor compartment are less in terms of their lengths than those of a motorcar (whose motor compartment is placed in front of the cabin), become widely spread.

Considering the above, increasing the safety of tractor-trailer operation remains a highly critical problem.

The analysis of trailer-related accident rate shows that the main reason of accidents is a loss of stability both at rectilinear (crossing over into the lane of oncoming traffic, driving off the road, etc.) and curvilinear (losing longitudinal or transversal stability, crossing over into the lane of oncoming traffic, overturning, etc.) movements on the road. In the absence of a unified theory of road motion for vehicles and trailers, analyzing the main factors which influence their stability in maintaining a complex trajectory is extremely difficult in terms of mathematics. In that case, road motion is divided into two simple types: rectilinear and curvilinear (cornering) ones. In practice, one basic factor which checks (regulates) the risk level is a speed limit, especially that of tractor-trailers. In general, for each type of vehicles, motions and road conditions, there exist established standards of maximum speed, thus regulating the risk of accidents occurring. All other means of regulation (lane width, car clearance, type, number, design and location of wheels, tyre material, road curve radius, etc.) have been strictly specified by corresponding normative documents with almost invariable values set for those factors.

Thus, in practice, the main mechanism of providing the traffic safety (maintaining the stable motion on a chosen trajectory) remains to be a speed limit, whose violation is registered as the main cause of most car accidents. More than that, accurate compliance with speed limits does not really guarantee the absence of accidents exactly because of the probability of losing stability or trajectory deviation.

For long-measuring motor- and tractor-trailers it is especially an essential issue [3-5]. The actuality of the issue rises with an increase in the tractor-trailer length (number and size of attached parts).

Based on the above it can be concluded that providing the motion stability of a tractor-trailer on a chosen (optimal) trajectory of the road is the main problem to be tackled if one wants to increase the traffic safety. And among others, there are two particular ways of doing so from the viewpoint of technically upgrading a trailer:

- increasing the stabilities of on-course movement and cornering;
- increasing the maneuverability of tractor-trailers.

In this case, the tractor-trailer motion stability means the absence of deviation from a given (optimal) motion trajectory of a tractor-trailer (all of its parts) while staying within the road lane (lane allocated to a vehicle).

The motion stability is one of the most important properties which impact the active safety. In practice, it is achieved as follows:

- selecting an optimal (in theory) motion trajectory– it is mostly provided by improving the skill and experience of a driver;
- maintaining the motion stability of a towing vehicle (car, tractor, etc.) – that issue was studied by many researchers [1, 4, 6];

- providing the motion stability of a towed vehicle (trailer) [2] – it allows one to maintain a given trajectory of both a tractor and its trailer in spite of active forces which provoke overturning, especially at high speeds.

In our opinion, the idea of improving the traffic safety for tractor-trailers by maintaining the motion stability of trailers is insufficiently explored. At the same time, losing such stability is the main reason of accidents involving trailers [5].

During the analysis of the problem it was noted that optimizing design and process parameters of towing and towed vehicles (tractors and trailers) was virtually directed not at decreasing the number of accidents with them (as those parameters are invariable), but rather at staying within a common trend which is highly unprofitable to break for technological, financial and other reasons. It should also be made clear that, unfortunately, this technical optimization does not actually provide the level of traffic safety needed, especially for trailers.

The authors made a conjecture about the possibility of increasing the traffic safety of tractor-trailers by improving their motion stability on the road trajectory, which could be achieved by redesigning the towing coupler mechanism (which connects different parts of a tractor and its trailer).

Thus, a scientific hypothesis proposed in this paper would be decreasing the accident rate for tractor-trailers by increasing their motion stability on the road via optimization of design parameters of the towing coupler.

2. Object and method of the research

Considering the above, we suggested that a rational solution which would increase the motion stability of tractor-trailers could redesign their towing couplers.

An important traffic-safety requirement for motor- and tractor-trailers is to observe the maximal lateral deviation caused by transverse oscillations (wandering) of a trailer. This type of stability loss expands the motion lane of a vehicle, leads to its sideslip and, thus, can pose a threat to oncoming and passing vehicles safety.

There are two types of mechanisms which are commonly utilized to steer the front wheels of biaxial trailers:

- a wheel turning mechanism by means of a steering linkage (similar to the one used in cars);
- and the one for wheels mounted on a rotating bogie connected to the trailer frame via a swivel (a large ball bearing).

One reason for motion stability loss (continuous lateral deviations) could be nonexistent or insufficient stabilization of the steering wheels of a trailer. Stabilization of the front wheels of a biaxial trailer should be considered as an ability to maintain a neutral position corresponding to linear motion and return on a chosen trajectory when external forces are withdrawn or even yet present.

For motor- and tractor-trailers equipped with a steering linkage, the stabilization of front wheels is achieved by providing casters to kingpins of steering knuckles [5]. It enables correct wheel rolling along the road and improves the stability, that is an ability to maintain a given course.

The kinematic diagram of a biaxial trailer with a swivel has a century-old history of usage, starting with horse carriages, whose swivels lied in a plane parallel to the bottom of a carriage, and since then there has not been much progress in this area. Stabilization mechanisms for the front wheels of swivel-based trailers are virtually omitted due to speed limits. And it is quite difficult to control a tractor-trailer with low stabilization because of its motion instability. According to [1, 4], a biaxial trailer can become unstable at 50 km/h. As a result, the operational safety of a swivel-based trailer (without taking the risk of losing the stability) is provided only by the speed limit mentioned.

Various electromechanical, hydraulic and other stabilizing devices are known from literature and patent sources to be used to stabilize front wheels of trailers equipped with a rotating bogie connected to the trailer frame via a swivel. Some of them are patented by the authors of this paper [7–15]. But those devices are rather difficult to manufacture and not reliable enough, that is why they are not widely used.

In our opinion, there are more promising and realizable designs of such devices for biaxial trailers and semi-trailers, whose kinematic schemes include a longitudinally inclined rotation axis (kingpin caster) of a swivel. Those particular steering devices are also patented by the authors [10–14].

The former designs of swivel-based biaxial trailers have not featured a kingpin caster μ . It can be provided by inclining a swivel in the longitudinal plane about the trailer frame. The caster may vary both by value and by sign. By convention, when the top half of the kingpin is closer to the back of the vehicle, the caster μ is positive. In such position, the caster purpose, in the case of spontaneous turning of the wheels in linear motion, is to form an arm, which is relative to the kingpin axis, of lateral reactions aimed to restore a neutral position of the wheels.

A similar kinematic scheme could be used for semi-trailers whose front side lies on a towing tractor. In this case, the slewing platform of the tractor (for example, a saddle of the towing coupler) and the kingpin of its semitrailer are inclined to the frame in the longitudinal plane. Figures 3–6 illustrate a semitrailer, biaxial trailer and partial-loading car-towing trailer with a kingpin caster and slewing platform.

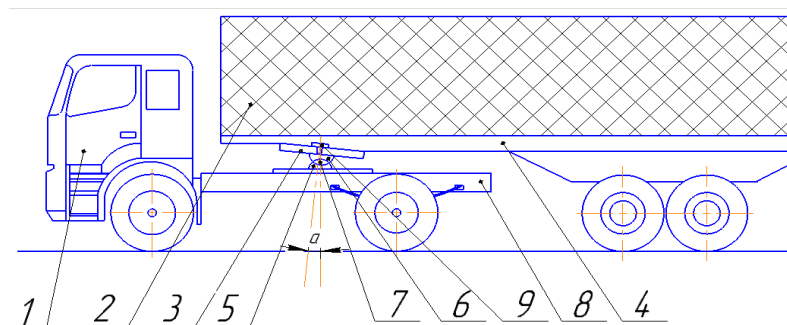


Figure 3. Tractor-trailer with semitrailer kingpin caster (1 – tractor; 2 – semitrailer; 3 – slewing platform; 4 – semitrailer frame; 5 – tractor frame bracket; 6 – slewing platform bracket; 7 – lateral axis of slewing platform; 8 – tractor frame; 9 – slewing platform kingpin; μ – kingpin caster).

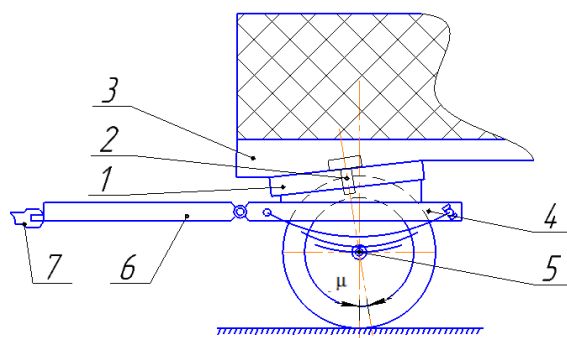


Figure 4. Leading bogie of biaxial trailer with negative caster of slewing platform (1 – slewing platform; 2 – kingpin; 3 – trailer frame; 4 – rotating bogie frame; 5 – axis of running wheels; 6 – towbar; 7 – towing attachment; μ – kingpin caster (negative)).

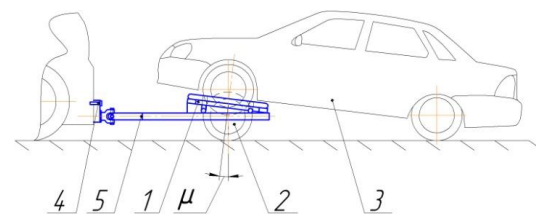


Figure 5. Partial-loading car-towing trailer with positive caster (1 – trailer frame; 2 – running trailer wheel; 3 – towed vehicle; 4 – towing attachment; 5 – towing lever; μ – imaginary kingpin caster (positive)).

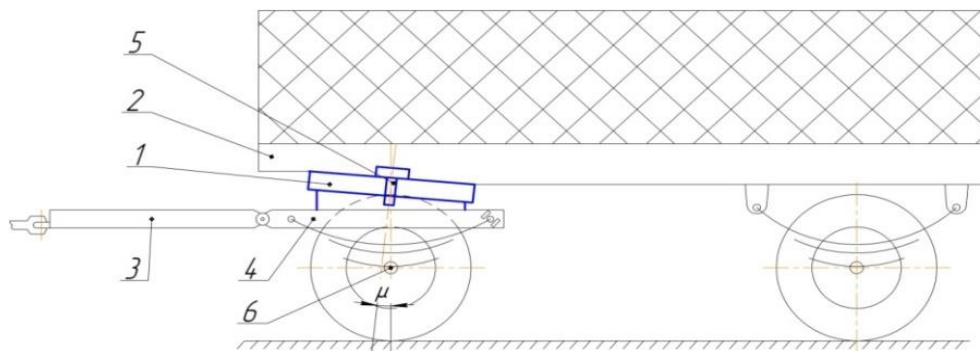


Figure 6. Slewing unit of biaxial trailer with kingpin caster (1 – swivel (slewing platform), 2 –trailer frame, 3 – towbar, 4 – frame of leading wheeled bogie, 5 – kingpin, 6 – axis of front trailer wheels).

Figure 6 shows the kinematic scheme of a biaxial trailer with a slewing unit which provides stabilization of the leading bogie wheels via positive caster. This slewing unit differs from a typical one in having its slewing platform (swivel) 1 mounted on a frame 4 of the bogie at an angle to the trailer frame 2 in the longitudinal vertical plane of the trailer. And the kingpin axis 5 is μ -inclined to a vertical line which goes through the middle of the axis of the leading bogie wheels and crosses the horizontal plane of motion at a point shifted forward in relation to the wheel axis. When the bogie and its wheel axis are turning, the caster leads to a stabilizing moment appearing, which helps to return the wheels to a neutral position corresponding to linear motion.

Figure 7 illustrates forces acting on the bogie wheels. The kingpin axis BC is inclined to the motion plane and forms an angle μ with the vertical line. The projection of the running axis on the motion plane forms an angle θ with that projection during linear motion.

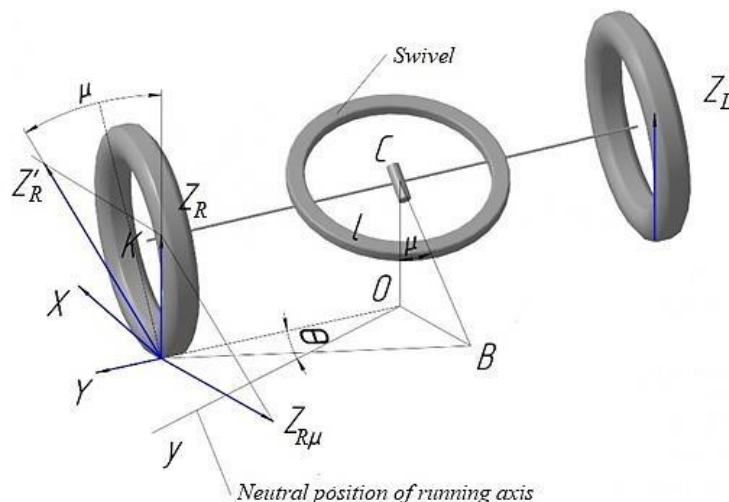


Figure 7. Forces acting on the wheel inner to the turning point of the bogie.

The authors described the method of determining the stabilizing moment and moments of road reaction on bogie wheels in another paper [16].

The following reactions act on the wheels of a bogie while it is turning:

- X – tangential reaction of the road (ground);
- Y – lateral reaction of the road (ground);
- Z_R – vertical reaction of the road (ground).

$$M_Y = L \cdot Z_R \cdot \sin^2 \theta \cdot \sin^2 \mu \cdot \cos(\arcsin(\sin \theta \cdot \sin \mu)) \cdot \operatorname{tg} \mu \cdot \cos \theta, \quad (1)$$

$$M_X = Z_R f \cdot \left(\sqrt{(L \cdot \sin \theta \cdot \sin \mu)^2 - (L \cdot \sin \theta \cdot \sin \mu \cdot \operatorname{tg} \mu \cdot \cos \theta)^2} + L \cdot \cos(\arcsin(\sin \theta \cdot \sin \mu)) \right), \quad (2)$$

$$M_{ZR} = L \cdot Z_R \cdot \cos \theta \cdot \operatorname{tg} \mu. \quad (3)$$

Also, the moment of tyre-turning resistance M_T acts on an elastic-tyre wheel due to displacements of X and Y reactions from the center of contact when the wheel is slipping. The moment of tyre-turning resistance M_T is taken from experimentally-obtained data of [1, 3]. The relation between M_T and the turning angle θ is shown in figure 8.

3. Research results

Let us consider the behavior of stabilizing moments M_{ZR} , M_X , M_Y and M_T from an example on a 2-PTS-6 tractor-trailer with a swivel which allows the leading bogie to make a turn of up to 90° relative to the body frame. Assumptions are: absolutely rigid suspension of the leading bogie; no torsion deformation of the trailer frame; no lateral skidding of tyres; fully-laden trailer. The kingpin caster μ is set to 5° . Under those conditions, when the bogie is turning, the wheel outer to the turning point is detached from the ground, and all the load from the trailer weight applied to the bogie moves away to the wheel inner to the turning point. It is not a typical situation in the operation of tractor-trailers since a spring suspension, frame torsion, elasticity of wheels provide their constant contact with the road. We assume that the reaction moment Y , acting along the running axis, is negative since the direction of forces from Y causes a moment which impedes the moments M_Z , M_X , M_T , all combined into the total stabilization moment M_{ST} . A wheel equipped with an elastic tyre is also acted on by the tyre-turning resistance moment M_T , which appears as a result of the displacements of X and Y reactions from the center of contact. That moment is taken from experimental data in [4, 5].

Figure 8 demonstrates how the moments M_Z , M_X , M_Y , M_T and the total stabilization moment M_{ST} relate to the angle θ of the bogie turning about the trailer frame.

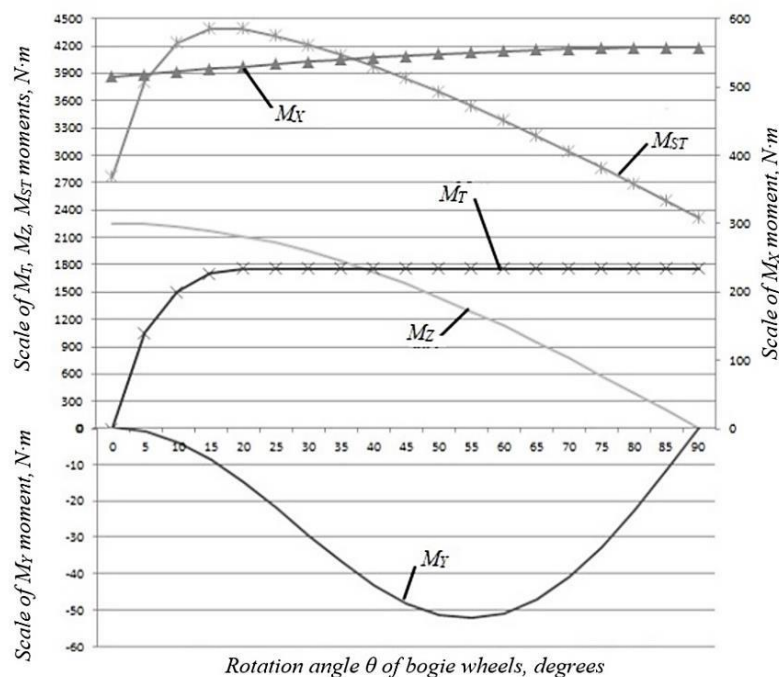


Figure 8. Stabilization moment and its components.

Analysis of the diagram allows one to draw the following conclusions:

- upgrading a biaxial trailer by designing a kingpin caster for its bogie swivel leads to appearance of such force reactions and moments which stabilize the motion of its front wheels, thus, helping to maintain a neutral position corresponding to linear motion;
- at road bends it also leads to redistribution of the load from the trailer weight towards the wheel inner to the turning point, which helps to resist an overturning impulse caused by centrifugal forces and increase the maneuvering safety of the tractor-trailer.

Preliminary tests were conducted on a scaled model of a biaxial tractor-trailer in order to prove the accuracy of the theoretical results on the impact which the caster has on stabilization of biaxial trailer motion.

A 1:13 scaled model of a 2-PTS-6 tractor-trailer (figure 9) was constructed for the tests. The model is equipped with a swivel mounted on the leading bogie and a screw mechanism, which enables to adjust the caster steplessly, thus allowing to carry out experiments at different angles μ of the kingpin.



Figure 9. 1:13 scaled model of biaxial tractor-trailer: a) tractor with biaxial trailer; b) adjustment of the kingpin caster (swivel inclination) of the leading bogie.

The testing was held on a belt imitating a conveyor with an electric drive and stepless regulator of the drive frequency and linear belt velocity.

The experiment was carried out as follows. The scaled model was placed on the conveyor belt, the tractor was fixed by a rope, preventing its longitudinal movement along the belt, and the caster was set with the help of the screw mechanism (figure 9b).

After a given belt speed was reached, certain lateral pressure was applied to the trailer to deviate it towards the belt edge. When the pressure was terminated, lateral deviations of the trailer and tractor-trailer as a whole were filmed by a high-speed video camera installed at the belt end. The analysis of those recordings allows to determine the amplitude of the lateral deviations (wandering) of the trailer, their frequency and damping time and use them as estimation criteria.

The results of this data processing allowed to compare, by analyzing the behavior of transverse oscillations caused by external lateral pressure and assessing the motion stability, two schemes of a biaxial trailer – a conventional one (with a swivel parallel to the trailer frame and no kingpin caster). They also showed that, at the belt velocity of 42 km/h, lateral deviations of a conventional trailer (with no kingpin caster) showed damped behavior after application of lateral pressure and faded completely after 7 seconds on average (figure 8).

When the caster was set to 6° , the lateral pressure had no effect on the trailer at all as far as transverse oscillations were concerned – the trailer returned smoothly to its initial trajectory, thus achieving absolute motion stability.

4. Conclusion

The study which was carried out helped to establish that the main reason of quite a large number of road accidents involving tractor-trailers is a loss of their motion stability on the road. A conventional method of preventing the accidents is setting a speed limit; however, it does not guarantee any acceptable result. Other ways of resolving this issue have almost exhausted their potential. It should be noted that solving this problem is further complicated by a lack of a unified road-movement theory for tractor-trailers – thus, mainly restrictive measures are used.

The authors suggested a hypothesis on possible improvement of tractor-trailer safety by means of increasing their motion stability via upgraded design characteristics of towing tractor-trailer couplers. The higher stability would be achieved by raising the damping factor of transverse oscillations by applying lateral disturbing forces.

The authors proposed over 55 technical solutions, all protected by certificates of authorship in engineering, of upgrading the towing couplers and providing the increase of tractor-trailer operation safety in various road conditions.

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